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Determining the heat flow through the cabinet walls of household refrigerating appliances

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Highlights

- A measurement method for determining the $k \cdot A$ value of household refrigerating appliances is presented.
- A latent heat sink is a suitable alternative to the reverse heat leak method.
- Air flow and storage temperatures in the refrigerator compartment are comparable to the real operating conditions.
- Temperature gradients between the storage room and the ambient of the refrigerating appliances are more realistic.
- An age-related increase of the $k \cdot A$ value of between 3.6 % and 11.5 % is found over a period of 14 months.

Keywords

Household refrigerating appliances, PUR foam, $k \cdot A$ value, Insulation, Measurement method

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Abstract

The increase of the thermal conductivity of PUR foam in the insulation of the cabinet is an important cause for aging processes of household refrigerating appliances. To determine the influence of the PUR foam aging on energy consumption, the development of a new measurement method is necessary because current methods influence the aging behavior of household refrigerators and are therefore not applicable in general. Based on a latent heat sink, constructed as an ice water bucket, a new measurement method is developed to determine the $k \cdot A$ value over time. With this method, the $k \cdot A$ value of four household refrigerating appliances was determined over an interval of 14 months. The $k \cdot A$ value increased between 3.6 % and 11.5 % during this period.

Nomenclature

A	Surface (m^2)
A_a	Outer surface (m^2)
A_i	Inner surface (m^2)
A_j	Average surface of material layer j (m^2)
$c_{v,ice}$	Specific isochoric heat capacity of ice (kJ/(kg K)
d_j	Material thickness of layer *j* (mm)
k	Heat transfer coefficient (W/(m^2 K))
$(k \cdot A)_{total}$	$k \cdot A$ value related to the ice water bucket (W/K)
$(k \cdot A)_{ffc}$	$k \cdot A$ value related to the fresh food compartment (W/K)
m_{ice}	Mass of ice of the second addition (kg)
P_{pump}	Power of pump (W)
$\dot{Q}_{ice}$	Heat flow absorbed by the ice (W)
$\dot{Q}_{cab.}$	Heat flow through the cabinet (W)
$\dot{Q}_{total}$	Heat flow related to the ice water bucket (W)
$\dot{Q}_{ffc}$	Heat flow related to the fresh food compartment (W)
T_a	Ambient temperature (°C)
T_{ice}	Time averaged ice temperature (°C)
$T_{ice,i}$	Instantaneous ice temperature (°C)
$T_{ice,1}$	Storage temperature of the ice (°C)
T_i	Temperature inside (°C)
T_{ma}	Time averaged temperature of heat sink measurements (°C)
T_1	Temperature at measurement point 1 (°C)
T_2	Temperature at measurement point 2 (°C)
T_3	Temperature at measurement point 3 (°C)
α_a	Heat transfer coefficient outside (W/(m^2 K))
α_i	Heat transfer coefficient inside (W/(m^2 K))
Δh_m	Enthalpy of fusion of ice (kJ/kg)
$\Delta(k \cdot A)_{total}$	Measurement error related to the ice water bucket (%)
$\Delta(k \cdot A)_{ffc}$	Measurement error related to the fresh food compartment (%)
$\Delta(k \cdot A)_{max}$	Maximum measurement error (%)
$\Delta\tau_m$	Melting time (s)
ΔT	Temperature difference (K)
λ_j	Thermal conductivity of material layer (W/(m K))
λ_{PS}	Thermal conductivity of HIPS (W/(m K))
λ_{PUR}	Thermal conductivity of PUR foam (W/(m K))
λ_{ST}	Thermal conductivity of steel (W/(m K))

1 Introduction

Due to the increasing customer awareness of global warming and the necessary reduction of greenhouse gas emissions, the EU energy label has become an essential selling point for modern household refrigerating appliances [1]. It compares household refrigerating appliances with respect to their energy consumption, storage volume as well as construction type and classifies them according to their energy efficiency. For this purpose, standardized measuring methods are used to sample these quantities of new household refrigerating appliances. However, like any technical system, household refrigerating appliances are subject to considerable technical degeneration over their lifespan of up to 20 years in some cases. An Australian study from 1990 on household refrigerating appliances, most likely with CFC-containing PUR foams, showed no aging influence on energy consumption in the first two years [2]. Typically, CFC-11 was used in PUR foams at the time when that study was carried out [3-5]. First prototypes of CFC-free household refrigerating appliances were developed in 1992 [6]. Around 1994, the first models of this appliance type were brought into the market in significant numbers [7, 8]. Due to a low water content in the raw materials, CFC-containing PUR foams are typically less susceptible to aging processes than current state-of-the-art cyclopentane-blown PUR foams [9]. Elsner et al. showed an increase of energy consumption between 20 % and 35 % over a period of 18 years for household refrigerating appliances with PUR foams that do not contain CFC [10]. Harrington examined the influence of the energy saving potential by replacing old appliances through modern appliances [11]. The study showed that the replacement of older appliances has an energy saving potential of about 60 %. In his dissertation [12], Harrington examined the influence of consumer behavior on energy consumption of household refrigerating appliances. Among others, he determined the influence of temperature and humidity in the storage room, ambient temperature, evaporator defrosting, door openings and the general choice of the model. Wagner developed methods to simulate heat transfer through PUR foam as a part of his dissertation [13].

The method described in this paper is part of a larger project that aims to determine the energy consumption increase of new household refrigerators over a period of three years with non-destructive measurement methods.

1.1 Aging of PUR foams

With a share of 45 % to 55 %, the heat flow entering the storage room through the cabinet represents the largest driver for the energy consumption of a household refrigerating appliance [14]. The cabinet essentially consists of an approximately 1 mm layer of galvanized sheet steel on the outside, a 40-60 mm thick core made of PUR foam and an approximately 0.6-2 mm layer of high impact polystyrene (HIPS) on the inside towards the storage room. During the manufacturing process, isocyanates and polyols react in a polyaddition reaction to PUR. A second blowing reaction between isocyanates and water leads to CO_2-formation. The CO_2 and the additional physical blowing agent cyclopentane (isopentane) cause foam rise of the PUR. After the manufacturing process, the cell gas of the PUR foam primarily consists of CO_2 and cyclopentane. Through diffusion processes, CO_2 is replaced over time by nitrogen and oxygen from the ambient air [9, 15-17]. This leads to an increase of the thermal conductivity of the PUR foam (λ_{PUR}) and thus to an increase of the energy consumption of household refrigerating appliances [18-23]. This process is strongly dependent on the temperature that the PUR foam is exposed to [18-22]. Current research projects are examining the replacement of the blowing agent pentane with CO_2-water mixtures. However, this would not prevent aging due to diffusion processes, since CO_2 is also present in these PUR foam cells as a reaction product [17]. Instead, the aging problem would be exacerbated with a CO_2-water mixture as a blowing agent.

1.2 Heat transfer through the cabinet walls

The heat flow through the cabinet walls ($\dot{Q}_{cab.}$) can be expressed as a product of the heat transfer coefficient (k), the surface area over which the heat transfer takes place (A) and the temperature difference (ΔT) between the ambient (T_a) and the temperature inside the cabinet (T_i) of the household refrigerating appliance.

$$\dot{Q}_{Cab.} = k \cdot A \cdot \Delta T = k \cdot A \cdot (T_a - T_i) \tag{1}$$

The heat transfer coefficient k is constituted by the convective heat transfer coefficients on the outside (α_a) and inside (α_i) surface of the cabinet, the material thicknesses of the various layers of the wall structure (d_j) and the thermal conductivity of the materials (λ_j). Equation 2 also considers the typically different surface sizes of the outside (A_a) and inside (A_i) of the cabinet and the middle surfaces of the different material layers (A_j).

$$\frac{1}{k \cdot A} = \frac{1}{\alpha_a \cdot A_a} + \sum_{j=1}^{n} \frac{d_j}{\lambda_j \cdot A_j} + \frac{1}{\alpha_i \cdot A_i} \tag{2}$$

A schematic of the cabinet walls and the resulting temperature profile is shown in Figure 1. With increasing usage time, the thermal conductivity of the PUR foam (λ_{PUR}) increases, while the thermal conductivity of the galvanized steel sheet (λ_{ST}) on the outside and that of the HIPS inliner (λ_{PS}) remain constant. Consequently, the heat flow entering the cabinet increases and so does the energy consumption of the refrigeration process.

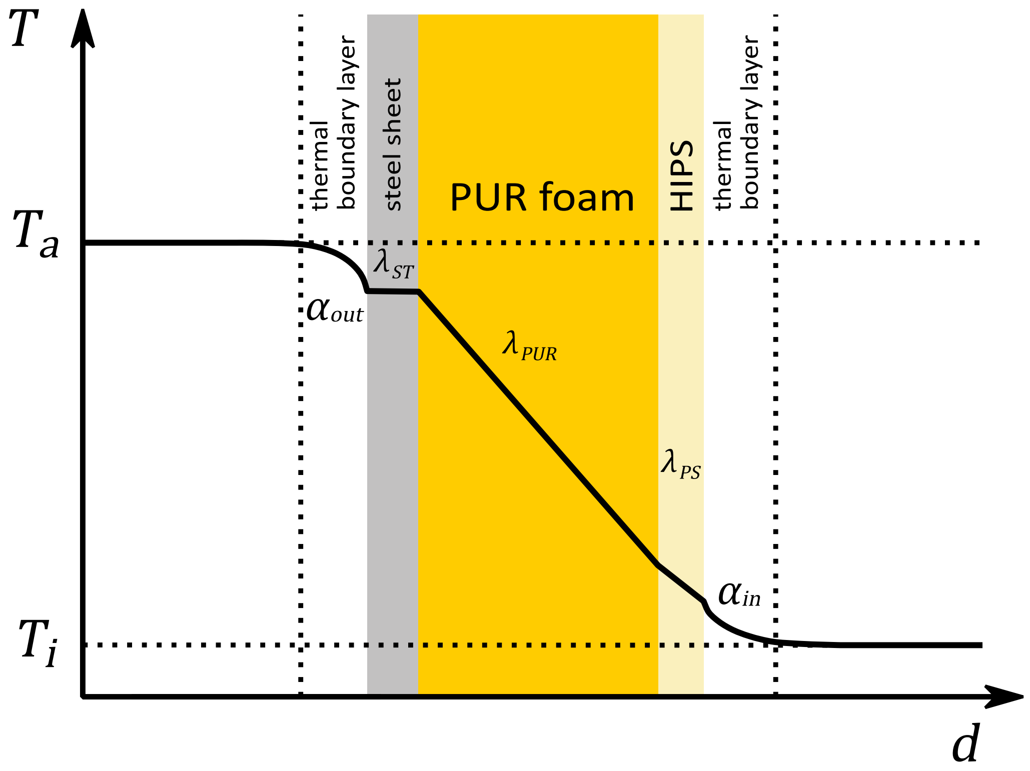

Fig. 1 **Schematic of the cabinet wall structure of a household refrigerating appliance with a qualitative temperature profile.**

1.3 Measurement methods for the $k \cdot A$ value

Several measurement methods to determine the heat flow through the refrigerating appliance cabinet walls have been proposed. Among them, the reverse heat leak method should be mentioned in particular. Various authors have reported on their investigations, modifications and improvements of the reverse heat leak method [24-28], which is also used in R&D departments of refrigerating appliance manufacturers.

In contrast to the usual temperature conditions in the storage room of a refrigerating appliance, heat is supplied to the interior of the cabinet by means of an electric heater, while the ambient temperature is reduced, so that a heat flow occurs from the inside out. The electrical heating power needed to maintain a stable temperature inside the cabinet is directly related to the heat flow through the cabinet walls.

However, in practice, there are several problems with this experimental setup:

- Using the reverse heat leak method repeatedly over a period of several years can lead to accelerated aging, as cell gas diffusion is temperature dependent and progresses more rapidly at elevated temperatures.
- In order to prevent temperature stratification in the interior, fans are used in the reverse heat leak method to achieve a more homogeneous temperature distribution. However, the fans create a forced air flow that differs from natural convection in real household use. This results in a larger convective heat transfer coefficient and the ageing-dependent thermal conductivity of the PUR foam can be falsified.

- Furthermore, the temperature difference between the storage room and the ambient differs from real household use, where the largest temperature difference occurs at the lower part of the storage room of the refrigerator, while the largest temperature difference is at the upper part of the storage room when the reverse heat leak method is used.

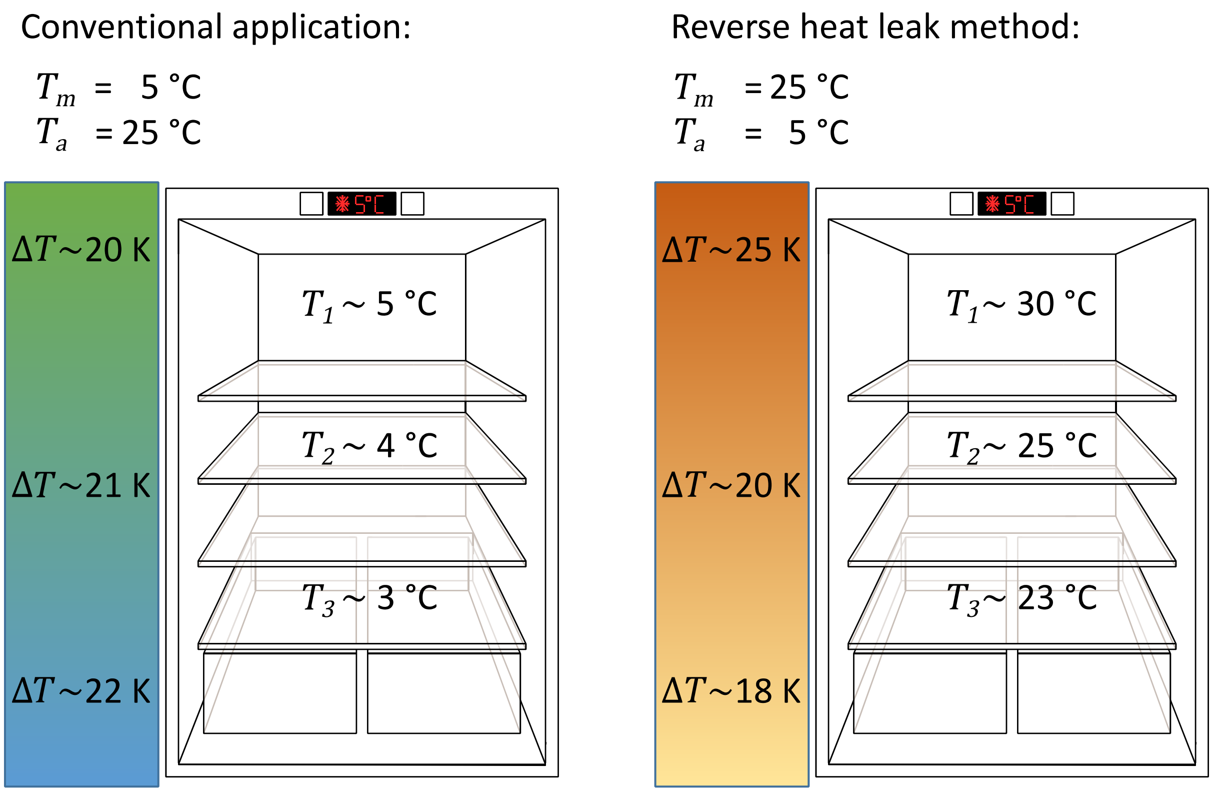

Fig. 2 Representation of the temperature gradient over a fresh food compartment during conventional use and reverse heat leak method measurement.

The heat flow can also be determined with heat flow sensors which are selectively placed on the cabinet. The functionality of the heat flow sensors was described by Lassue et al. [29]. Melo et al. investigated the use of heat flow sensors and compared the results with the reverse heat leak method [25]. This measuring method was further refined by Thiessen et al. [30].

However, the heat flow sensor measurement method also turned out to be unsuitable for the present project. Each refrigerating appliance has an individual cabinet design, depending on the manufacturer, brand, appliance type and condenser position arrangement. Cables and refrigerant pipes, which run through the PUR foam at various places, would have a strong impact on the results of this method.

Hueppe et al. [31] developed another measurement method. They determined the $k \cdot A$ value through the duration of a temperature rise in the storage compartments with a temperature rise test. In addition, aging tests on PUR foam samples have been published and show an increase of thermal conductivity of the PUR foam from 19.5 mW/(m K) to 22.5 mW/(m K) in 420 days.

2 Test setup

A non-destructive measuring method for the $k \cdot A$ value was developed in this work with the following aims:

The natural temperature stratification in the storage room of the refrigerating appliances and the temperature differences between the storage room and the ambient should be maintained as far as possible, natural convection should prevail in the storage room of the appliances and the measurement method should be integratable into the existing measurement setup of the standard energy consumption test according to the standard series IEC 62552:2015 (part 1 – part 3) with as little effort as possible [32-34].

2.1 Methodology

In the present latent heat sink measuring method, the refrigeration cycle of the appliance does not operate. Instead, the storage room of the appliance is cooled by a heat sink in the form of an ice water bucket (height 210 mm, diameter 254 mm) with a volume of 10.64 liters, cf. Figures 3 and 4. To achieve a homogeneous temperature distribution of the entire bucket surface, several cooling fins were attached to the lid, which protruded into the ice water. To avoid temperature stratification in the ice water, a pump was installed at the bottom of the tank to enforce circulation. The electrical power consumed by the pump was measured and taken into account in the energy balance for the calculation of the $k \cdot A$ value. To monitor the melting process of the ice water, four thermocouples were attached to the container, which protruded into the ice water at two different heights. Furthermore, surface temperatures of the tank were measured with two thermocouples and that of the lid with a third thermocouple.

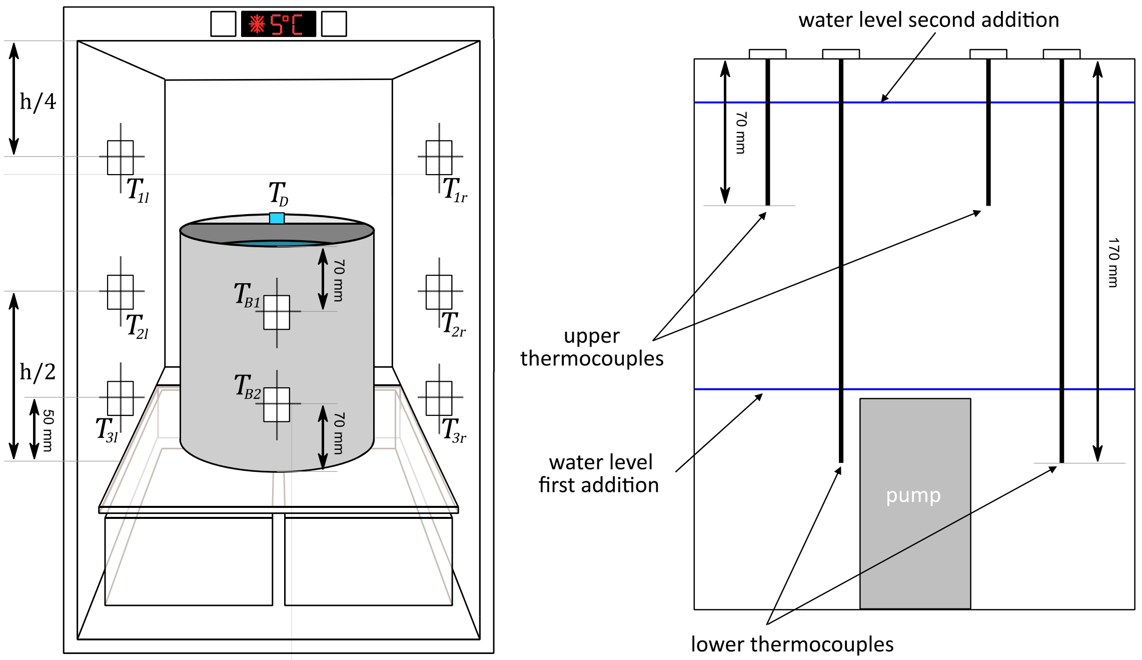

Fig. 3 Basic measurement setup in the fresh food compartment (left) and in the ice water bucket (right).

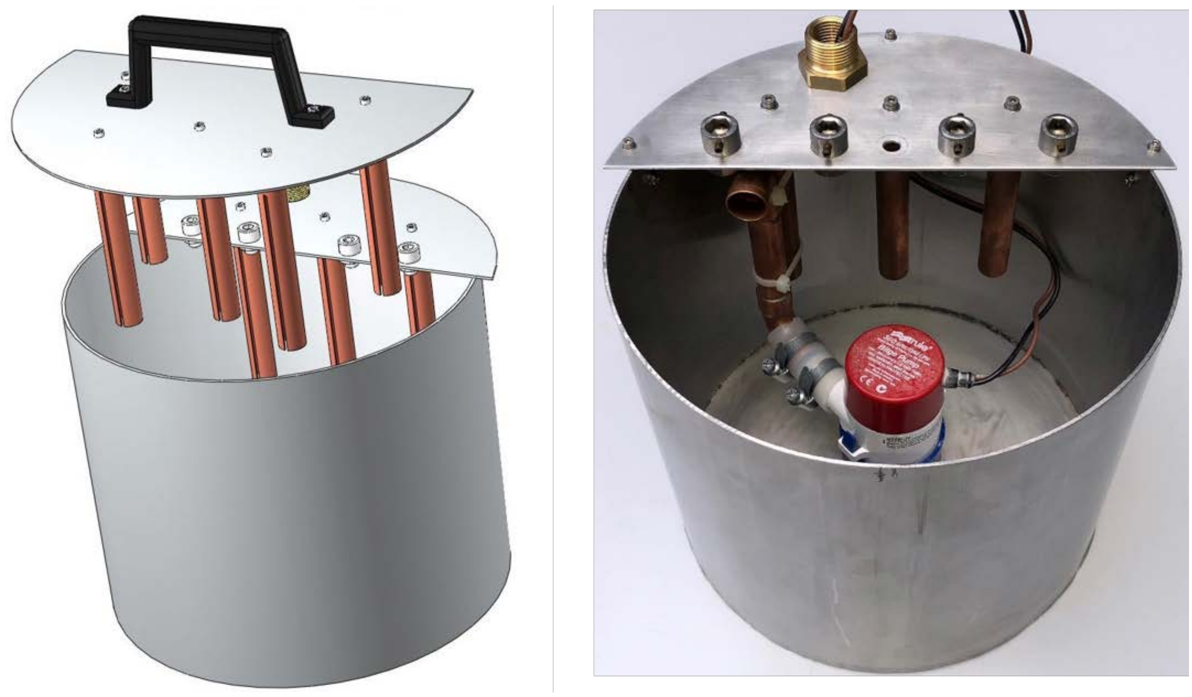

Fig. 4 Ice water bucket: technical drawing (left) and photo of the device (right).

Before the actual start of the experiment, the refrigerating appliance was operating at a time averaged fresh food compartment temperature of T_{ma} = 4 °C to 5 °C, which was determined as the mean value of the six temperature measuring points (T_{1l} to T_{3l} and T_{1r} to T_{3r}) located on both sides of the ice water bucket, cf. Figure 3. The measurements were made at ambient temperatures of 16 °C, 25 °C and 32 °C following the IEC 62552:2015 series of standards (part 1 and 3) [32, 34]. Depending on the ambient temperature, the ice water bucket was filled with an amount of liquid water as shown in Table 1 at the start of each measurement.

In principle, the experiment should measure the time required for the ice melting process, where the water temperature remains constant. The point in time at which there is no longer a temperature of 0 °C at all measuring points in the ice water can be seen as an increase in the temperature curve, cf. Figure 5. However, since there may still be residual ice in the bucket at this point in time, a solution had to be found to ensure that the amount of residual ice is the same at the start and the end of the measurement period. For this purpose, two ice additions were made.

First, a smaller amount of ice was added to the ice bucket. A relatively constant time period for the first melting phase could be achieved by varying this ice amount depending on the various ambient temperatures (cf. Table 1). During this phase in the experiment, the water level in the bucket only reaches the lower thermocouples, cf. Figure 3.

Table 1 - Comparison of the test parameters of the first ice addition under different ambient temperatures.			
Ambient temperature	16 °C	25 °C	32 °C
Mass of liquid water in the ice water bucket	4000 ± 20 g	3500 ± 20 g	3000 ± 20 g
Mass of the first addition of ice	1000 ± 20 g	1500 ± 20 g	2000 ± 20 g
Time of the first melting phase	7.00 - 7.75 h	6.75 - 7.50 h	7.00 - 7.75 h

When the lower thermocouples indicated that the temperature of the ice water had risen by 0.2 K, a second quantity of ice was added to the bucket and the actual measurement was initiated. The evaluation period ended when the average temperature of all ice water thermocouples again rose by 0.2 K. The evaluation period was thus the melting time ($\Delta\tau_m$). Figure 5 shows the temperature profile of the ice water over the course of a measurement.

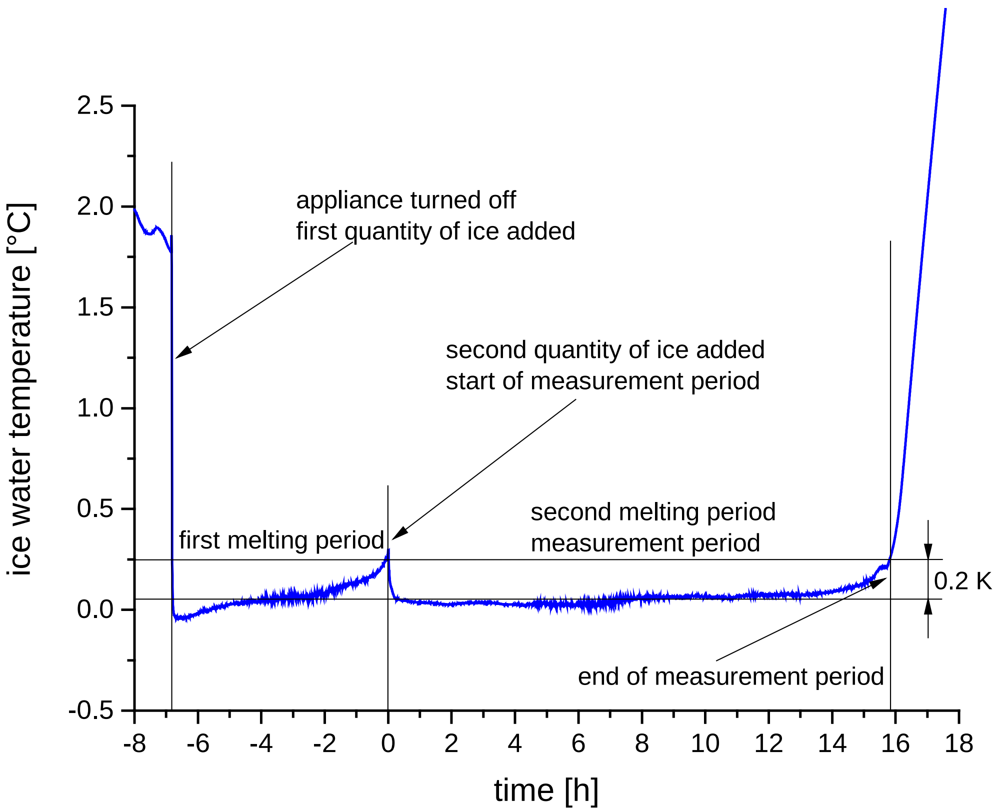

Fig. 5 Ice water temperature over time.

Validation tests were performed with a mass of 3500 g ice for the second addition and the measurements of the aging studies were performed with 3000 g to avoid overly long total measurement times.

2.2 Evaluation

By determining the time interval that the ice needs to melt ($\Delta\tau_m$), employing the enthalpy of fusion of water (Δh_m = 333.5 kJ/kg) and the mass of ice at the second ice addition (m_{ice}), the heat flow ($\dot{Q}_{ice}$) is given by equation 3. Since the ice was stored at temperatures below 0 °C ($T_{ice,1}$), the according enthalpy contribution was taken into account via the isochoric heat capacity of the ice ($c_{v,ice}$ = 2.204 kJ/(kg K)). The electrical power of the pump (P_{pump}) is dissipated by the circulation of the ice water and was considered in the energy balance.

$$(k \cdot A)_{total} = \frac{m_{ice} \cdot \left(\Delta h_m + c_{v,ice} \cdot \left(T_{ice} - T_{ice,1}\right)\right)}{\left(T_a - T_{ice}\right) \cdot \Delta\tau_m} - \frac{P_{pump}}{\left(T_a - T_{ice}\right)} \tag{3}$$

The equations presented in this way describe the $(k \cdot A)_{total}$ value for the heat flow entering the ice water through the appliance cabinet and the storage room. As shown in Figure 6, almost constant instantaneous temperatures (T_{ma}) were present in the storage room of the fresh food compartment during the tests. The balance between the heat flows $\dot{Q}_{cab.}$ and $\dot{Q}_{ice}$ remained practically constant until the end of the second melting phase. During the first melting phase, there was an increase of the instantaneous temperatures until a balance between the heat flow entering the storage room through the cabinet and the heat flow entering the ice water bucket from the storage room was established. The slightly lower instantaneous temperatures during the second melting phase can be explained by the higher degree of filling in the ice water bucket and the resulting larger surface of the bucket wetted by ice water.

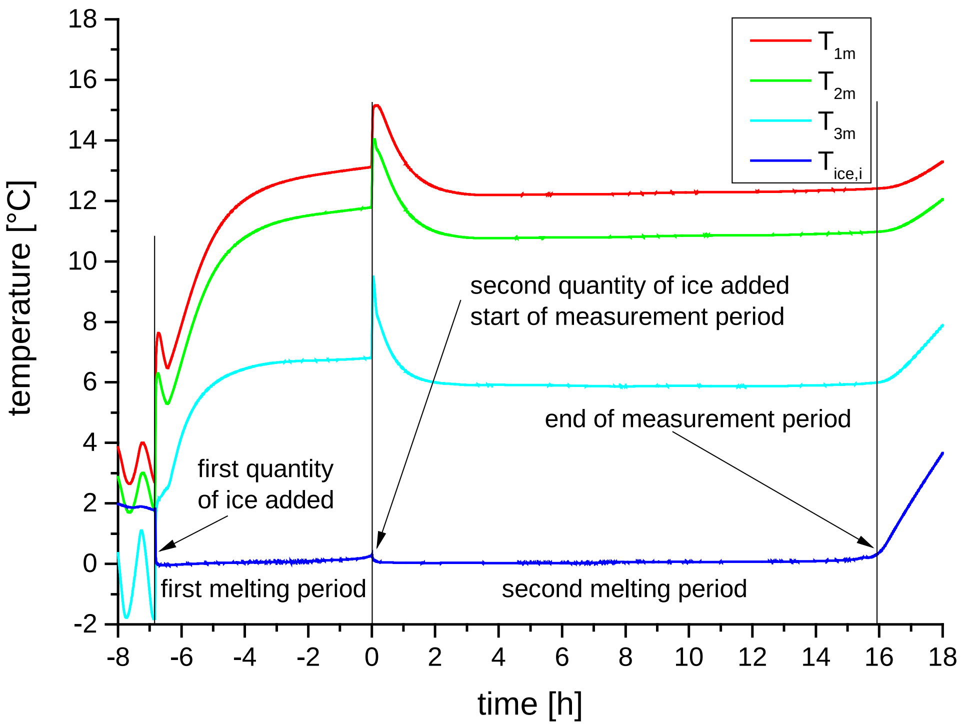

Fig. 6 Temperature at the measuring points in the fresh food compartment over time.

Constant instantaneous temperatures in the fresh food compartment allow for the replacement of the ice water temperature with the instantaneous temperature of the fresh food compartment in equation 3 so that the $(k \cdot A)_{ffc}$ value related to the refrigerating appliance cabinet can be determined (cf. equation 4). For this purpose, the ice water temperature in the denominator is replaced with the average fresh food compartment temperature.

$$(k \cdot A)_{ffc} = \frac{m_{ice} \cdot \left(\Delta h_m + c_{v,ice} \cdot \left(T_{ice} - T_{ice,1}\right)\right)}{(T_a - T_{ma}) \cdot \Delta\tau_m} - \frac{P_{pump}}{(T_a - T_{ma})} \qquad (4)$$

2.3 Refrigerating appliances

For a validation of the present measurement method, a commercially available table-height refrigerator (Miele, type K12020 S-1) was used. This appliance (V1) was chosen due to its age of five years. The investigations discussed in section 1 show that the most pronounced aging effects occur in the first three years [10, 18-23]. Thus, only small changes of the $k \cdot A$ value were expected for this appliance. In addition, aging tests were carried out for four refrigerators (R1 to R4), cf. Table 2. Contrary to the requirements of the standard IEC 62552-1:2015, part1, [32] the built-in refrigerators were operated without wooden cabinets in order to exclude any influences of the wood on the measurement results.

Table 2 - Technical data of the studied refrigerating appliances.

Test device		V1	V2	R1	R2	R3	R4
Refrigerator model		K12020 S-1	KI81RAD 30/04	KS 16-1 RVA+++	KS 16-1 RVA+++	KI81RAD 30/04	KI81RAD 30/04
Manufacturer		Miele	Siemens	Exquisit	Exquisit	Siemens	Siemens
Refrigerator type		table-height refrigerator	built-in refrigerator	table-height refrigerator	table-height refrigerator	built-in refrigerator	built-in refrigerator
Dimensions (HxWxD)	[mm]	850 x 601 x 628	1775 x 560 x 550	845 x 555 x 575	845 x 555 x 575	1775 x 560 x 550	1775 x 560 x 550
Total storage volume	[l]	167	319	134	134	319	319
Refrigerant		22 g R600a	46 g R600a	26 g R600a	26 g R600a	46 g R600a	46 g R600a
Energy label		A+	A++	A+++	A+++	A++	A++

2.4. Measurement system and measurement error analysis

The mass of water and ice was measured with a laboratory scale DE350.5D (Kern & Sohn GmbH) with an accuracy of ± 2.5 g. Temperatures were sampled by thermocouple differential measurements, where each measuring point had its own reference junction in a separate ice water bath. The measurement signal of the thermocouples was processed by a combination of a pre-amplifier LTC1050 (Linear Technologies) with adjusted gain of 1000 and a digital-to-analog converter system OMB-DAQ 55/56 (Omega Technologies), limiting the offset drift to ± 0.025 K. By calibrating each thermocouple individually and applying a polynomial correction, the measurement error was reduced from ± 1% x ΔT to ± 0.5% x ΔT. All measurements were carried out in a climatic chamber with an ambient temperature fluctuation of ± 0.5 K and an air humidity of 50 %. The supply voltage of the pumps was provided by BT-305 laboratory power supplies (BASETech) with ± 1 % + 0.02 V accuracy and the electric current with ± 2 % + 0.02 A. Due to cable length, the supply voltage at the pump was 1 % lower than the output of the power supply, which was taken into account in the calculations. The pumps (Bilge pump 360GPH) were operated with a supply voltage of 5 V. In preliminary tests, this turned out to be the best compromise between the heat introduced by the pump and the necessary circulation of the ice water to prevent temperature stratification in the bucket.

The measurement errors of the various devices are summarized in Table 3. The fluctuation of the ice storage temperature ($T_{ice,1}$) was assumed to be ± 1 K due to transportation and handling of the ice prior to the addition process. The measurement errors $\Delta(k \cdot A)_{total}$ and $\Delta(k \cdot A)_{ffc}$ were calculated with the error propagation law.

Table 3 – Measured properties and their uncertainties.		
Measured quantity	Measuring device	Uncertainty
Temperature	Thermocouples	± 0.1 K
Voltage	Laboratory power supplies	± 1 % + 0.02 V
Electric current	Laboratory power supplies	± 2 % + 0.02 A
Time	Personal computer	± 0.1 s/day
Mass	Laboratory scale	± 2.5 g

3. Results and discussion

3.1. Validation

For validation, five measurements for each ambient temperature of 16 °C, 25 °C and 32 °C were carried out with refrigerating appliance V1. The aim was to check the reproducibility and the influence of the ambient temperature on the results. In addition to the measured values and the results for the $k \cdot A$ values of the individual measurements, the total measurement errors $\Delta(k \cdot A)_{total}$ and $\Delta(k \cdot A)_{ffc}$ are specified in the following.

Overall, the data show a homogeneous distribution of the measurement results with a scatter on the same order of magnitude as the overall measurement error. As shown in Table 4, no influence of the ambient temperature on the measurement results was found.

Table 4 - Results of the validation test series with varying ambient temperature.					
Test series			16 °C	25 °C	32 °C
Ambient temperature	T_a	[°C]	15.7	24.8	31.8
Mass of the second addition of ice	m_{ice}	[g]	3489.0	3490.5	3493.5
Evaluation period	$\Delta\tau_m$	[h]	22.81	15.83	12.90
Average fresh food compartment temperatures	T_{m*}	[°C]	6.3	9.8	12.8
Power of the pump	P_{pump}	[W]	4.35	4.35	4.29
$(k \cdot A)_{total}$		[W/K]	0.74	0.75	0.75
$\Delta(k \cdot A)_{total}$		[%]	1.9 %	1.2 %	0.9 %
$(k \cdot A)_{ffc}$		[W/K]	1.22	1.24	1.25
$\Delta(k \cdot A)_{ffc}$		[%]	1.3 %	0.8 %	0.6 %

Despite the relatively constant results at different ambient temperatures, an ambient temperature of 25 °C was preferred for this measurement method. At an ambient temperature of 16 °C there are significantly higher measurement errors (± 1.9 %) and a time of more than 24 h for an entire test (first and second addition of ice) leads to additional organizational effort in labor operation. In addition, only for this ambient temperature, it was observed that an ice layer formed in the bucket on the water surface. A comparison of the ambient temperatures of 25 °C and 32 °C shows that the measurement error is lower at 32 °C, but the internal temperatures were significantly higher than in regular refrigerator operation. Table 5 shows the selection criteria mentioned for the evaluation of the three ambient temperatures.

Table 5 - Evaluation for the selection of the ambient temperature.

Ambient temperature		16 °C	25 °C	32 °C
Measurement error	$\Delta(k \cdot A)_{max}$	± 1.9 %	± 1.2 %	± 0.9 %
		-	0	+
Measurement time	second melting interval ($\Delta\tau_m$)	22.80 h	15.63 h	12.90 h
	total	30.50 h	23.00 h	20.50 h
		-	0	+
Ice layer on the water surface		yes	no	no
		- -	+	+
Average fresh food compartment temperature	T_{m*}	6.3 °C	9.9 °C	12.8 °C
		+	0	- -

3.2 Aging studies

With the present measuring method, the aging of commercially available refrigerating appliances was investigated shortly after their manufacturing. For this purpose, two tests per appliance were carried out on four appliances at an interval of 14 months and the $k \cdot A$ value was determined. The results are listed in Table 6. Figure 7 shows the results for the $(k \cdot A)_{total}$ value and the $(k \cdot A)_{ffc}$ value. The results indicate an increase between 3.6 % and 11.5 % for $(k \cdot A)_{total}$ and an increase between 6.1 % and 11.3 % for $(k \cdot A)_{ffc}$. This difference between the $k \cdot A$ values is significantly larger than the measurement error ($\Delta(k \cdot A)_{max}$ < 2 %). Hueppe et al. [31] investigated the change of the thermal conductivity of PUR foam samples over time and observed an increase of about 15 % over a period of 420 days. The determined increase of the $k \cdot A$ value of real refrigerating appliances is of similar magnitude.

Table 6 - Results of the aging study of refrigerating appliances.						
Test device			R1	R2	R3	R4
Refrigerator model			KS 16-1 RVA+++	KS 16-1 RVA+++	KI81RAD 30/04	KI81RAD 30/04
Manufacturer			Exquisit	Exquisit	Siemens	Siemens
$(k \cdot A)_{total}$	new	[W/K]	0.56	0.53	0.82	0.78
	after 14 months	[W/K]	0.58	0.58	0.88	0.87
	difference	[W/K]	+ 0.02	+ 0.05	+ 0.06	+ 0.09
		[%]	+ 3.6%	+ 9.4%	+ 7.3%	+ 11.5%
$(k \cdot A)_{ffc}$	new	[W/K]	0.82	0.78	1.65	1.60
	after 14 months	[W/K]	0.87	0.86	1.79	1.78
	difference	[W/K]	+ 0.05	+ 0.08	+ 0.14	+ 0.18
		[%]	+ 6.1%	+ 10.3%	+ 8.5%	+ 11.3%

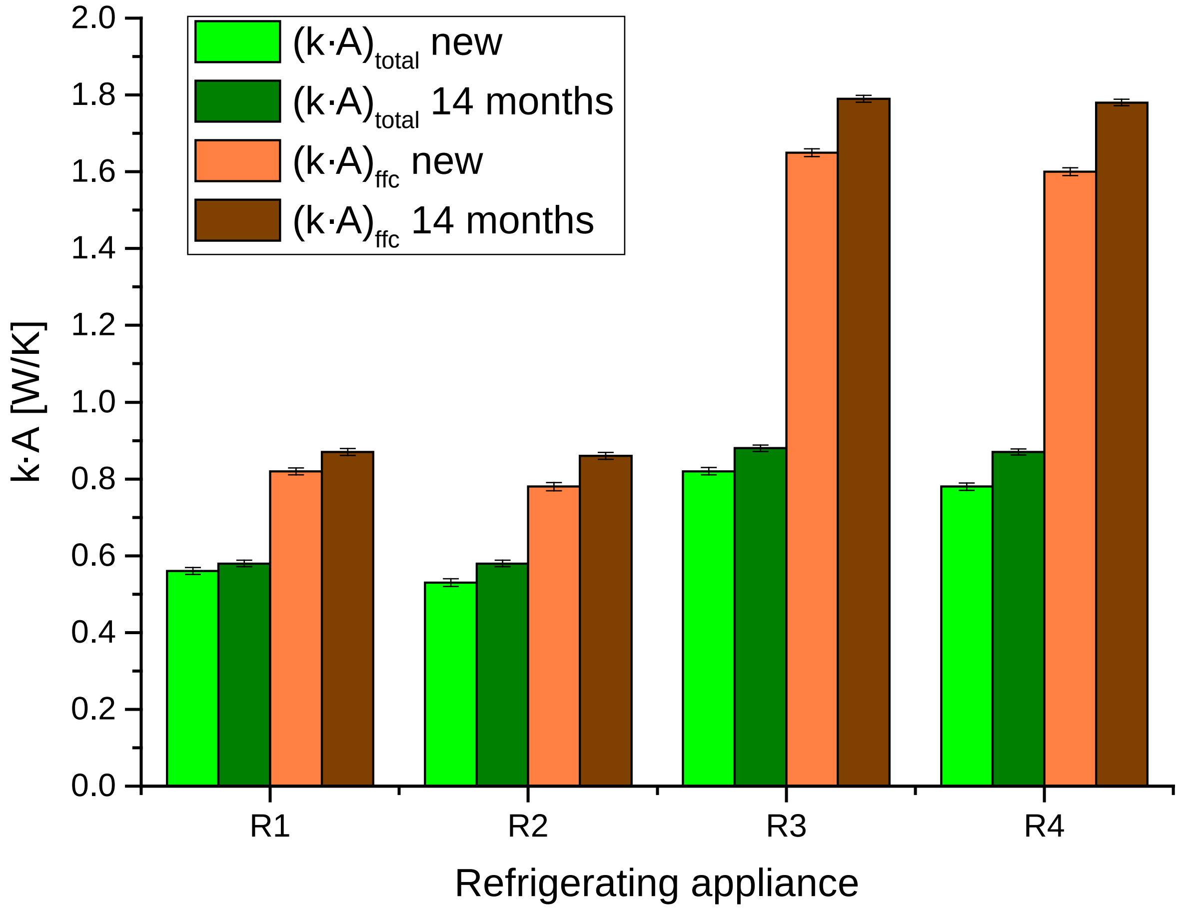

Fig. 7 Results of the aging study for $(k \cdot A)_{total}$ (green) and $(k \cdot A)_{ffc}$ (brown).

4 Conclusions

The presented experimental method with a latent heat sink is a suitable alternative to the reverse heat leak method for determining the heat flow into the cabinet of a refrigerating appliance. The advantage of the latent heat sink method is that the air flow and the temperatures in the storage room are comparable to the real operating conditions. The usage of fans in the reverse heat leak method generates locally turbulent flows, which increase convective heat transfer. The temperature gradient between the storage room and the ambient is also more realistic.

An ambient temperature of 25 °C was found to be optimal for using the latent heat sink method. Application-related temperatures are reached in the storage compartments, the measurement error is small and the total measurement time can be integrated into a 24 h cycle. An ambient temperature of 32 °C should not be chosen due to the higher storage temperature in the compartment and 16 °C should not be chosen due to the possible formation of ice layers.

By measuring the $k \cdot A$ value of new refrigerating appliances over time, an increase of 8.2 % (± 2.1 %) for the table high refrigerators and 9.9 % (± 1.4 %) for the large built-in refrigerators was found over a period of 14 months. This result is consistent with the literature for the increase of the thermal conductivity of PUR foam.

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